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RECENT PROGRESS IN HEAVY-ION FUSION IN THE U.S.

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ABSTRACT

Recent developments in accelerator physics and technology have led to lower cost estimates for a heavy-ion induction linac driver.

Studies show that the cost of electricity produced using such a driver are competitive with other fusion systems at a plant capacity of 1.2 GW_e and are competitive with projected fission power costs at less than 4 GW_e.

The HIBALL studies[1,2] reported in 1981 and 1984 were the first detailed studies of a heavy-ion fusion power plant. These studies were very important because they did much to establish the technical and economic feasibility of heavy-ion fusion. However, the HIBALL studies showed economic production of electricity only at large plant capacity ($\sim$4 GW_e), primarily because of the high cost of the radio frequency accelerator driver.

In the U.S., there has been some concern that plants as large as 4 GW_e might not be attractive to the power industry. Therefore, during the last two years, the heavy-ion fusion program in the U.S. has emphasized research that might lead to economic feasibility at smaller capacity and cost.

The U.S. approach to heavy ion fusion uses an induction linac driver. Figure 1 shows schematic diagrams of induction and radio frequency (r.f.) driver systems. The induction system is conceptually simple. It consists of one or more beam lines threading common induction cores that are pulsed as the beam passes.

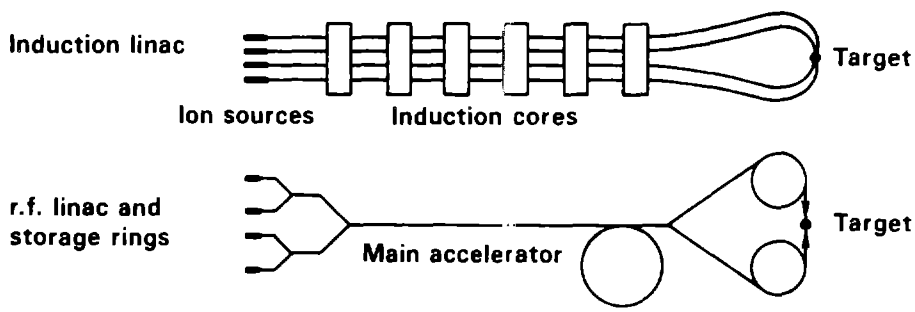

Fig. 1. Induction linac driver and r.f. linac and storage ring driver. In the induction case, multiple beams thread common cores. Four beams are shown.

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In simple terms the cores are a series of electrical transformers with the beams as secondary windings. The r.f. system is more complicated. The beams from multiple ion sources are merged and then accelerated as a single beam in the main r.f. accelerator. The current carrying capacity of an r.f. linac is substantially less than that of an induction linac. It is therefore necessary to provide storage rings and bunching rings to increase the current to that required by the target.

Some current amplification is also required for the induction approach. This amplification is obtained by accelerating the tail of the beam to a slightly higher speed than the head of the beam so that the beam compresses as it approaches the target. In some cases, it might also be desirable to merge beams in the induction linac. Nevertheless the induction system remains simpler than the r.f. system. We hope that this simplicity will lead to lower cost. In fact, early cost estimates did indicate that the cost of an induction system would be roughly 80% of the cost of an r.f. system,[3] but the cost was still too high for economic power production at small plant capacity.

Faced with the situation described above, we have attempted to reduce the cost of the induction linac by variation of accelerator parameters, improvements in targets, and improvements in accelerator technology. We have also considered novel accelerator concepts such as recirculating linacs and multiple pulsing where two or more pulses from the same accelerator are simultaneously brought to the target by an appropriate set of delay lines.

So far our work on improved targets, improved accelerator technology, and novel accelerator concepts is incomplete and has not led to lower costs. We are still hopeful that additional work will lead to significant cost reductions. By contrast, our work in variation of accelerator parameters has been very fruitful. In particular we found that increasing the charge state of the heavy ions from the value of $Q = 1$ assumed in many earlier studies to $Q = 3$ dramatically decreases the cost of the accelerator.

It had previously been recognized that higher charge states might be advantageous, but they had not been considered completely feasible for several reasons. Adequate ion sources for $Q > 1$ were not available. It had been considered possible to accelerate the beam to some velocity and then strip it to $Q > 1$ by sending it through some material, but stripping degrades the beam quality. In addition, analytic theory performed in the 1970's showed serious beam instabilities at the high electrical currents implied by high charge states. It also appeared difficult to focus beams with Q > 2 because of the repulsive effects of high charge density. Finally it appeared that Q > 2 would lead to instabilities in the storage rings of the r.f. systems.

The situation has changed. New metal arc ion sources show promise for Q > 1. Experiments and numerical simulations show that beam instabilities are more benign than previously believed. It appears possible to focus Q > 2 by neutralizing the beam with electrons. Finally we note that induction linacs don't require storage rings so that there are no worries about ring instabilities. However beam compression does appear to be more difficult at Q = 3 and we are continuing to study this problem.

All of the developments described above will be documented in the Proceedings of the 1986 International Symposium on Heavy Ion Fusion[4] held May 27-29, 1986 in Washington, D.C. The net result of the developments described above is the large reduction in driver cost shown in Table I.

Using the new driver costs, Lawrence Livermore National Laboratory performed a systems analysis giving the cost of electric power for the Livermore CASCADE reactor and an induction linac driver. The results are shown in Table II. Note

Table I. Comparison of 4.25 MJ induction linac drivers for charge state +1 and +3.

	Charge	Ion energy (GeV)	Length (km)	Efficiency (%)	Cost (G$)
Old	+1	~10	~11	25	1.2
New	+3	~10	~3*	35	0.5

*** The new design has a higher acceleration gradient**

Table II. Cost of electricity for several fusion power plants. HIF/CAS refers to the heavy-ion driven power plant using the Livermore CASCADE reactor.

	Net electric power: 1200 MW_e			3784 MW_e	
	STARFIRE	MARS	HIF/CAS	HIBALL-II	HIF/CAS
Direct cost (G$)	2.07	2.24	1.83	4.80	3.43
Total cost (G$)	3.78	4.10	3.34	8.78	6.30
COE (¢/kW_eh)	6.13	6.33	5.14	4.59	3.07

All costs in constant 1985 dollars.

that at 1.2 GW_e the cost of electricity (COE) for the heavy ion system (HIF/CAS) is less than the COE for STARFIRE (Tokamak) and MARS (Tandem Mirror), the two magnetic systems shown for comparison. Also note that at 3.8 GW_e the COE is less than the COE for HIBALL-II. Furthermore the COE is less than the COE of about 3.5¢/kW_eh expected from future 1-GW_e fission power plants.

In our studies we found that the COE is rather insensitive to assumptions about target gain. Increasing or decreasing the target gain by a factor of two results in less than a ±10% change in the COE.

Finally we note that until recently a multiple beam ion induction linac had never been built. A four beam test accelerator (MBE-4) is currently being built at Lawrence Berkeley Laboratory. The MBE-4 will not have sufficient energy to implode a target, but it will address important accelerator questions. For example, the longitudinal beam compression necessary for current amplification has recently been demonstrated with the portion of MBE-4 that is now in operation.

In conclusion, recent advances in accelerator physics and technology have enabled us to reduce the projected cost of an induction linac driver by more than a factor of two. The projected cost of electricity produced using such a driver is competitive with other fusion systems at 1.2 GW_e and is competitive with projected fission power costs at less than 4 GW_e.

References

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